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APPLICATION NUMBER: *09/223,887*
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Attorney Docket No.: TH-1457 (US)
A Named Inventor/Application Identifier: C. A. Tjeenk Willink
Express Mail Label No.: EM006402909US
Title: DEHYDRATION OF GASES AT A WELLHEAD
Date: December 31, 1998

UTILITY PATENT APPLICATION TRANSMITTAL
UNDER 37 CFR 1.53(b)

Assistant Commissioner for Patents
Box Patent Applications
Washington, DC 20231

1. ☒ This application is a(n):
   - a. ☒ Original
   - b. ☐ Continuation-in-part of Application Serial No. ______ filed ________
   - c. ☐ Divisional of Application Serial No. ________ filed ________
     - ☐ Applicant(s) elect the invention of Group/Species ________
   - d. ☐ Continuation of Application Serial No. ______ filed ________

2. ☒ Specification
   - a. ☒ Pages 24
   - b. ☒ Drawing, Total sheets 5

3. ☐ Oath or Declaration
   - a. ☐ Newly executed (original or copy)
   - b. ☐ Copy from a prior application
     - ☐ Please delete the following named inventors in the prior application: ________________

4. ☐ Please amend the specification
   - a. ☐ By inserting before the first line:
     This is a ☐ continuation ☐ division ☐ continuation-in-part of Application Serial No. ___________ filed ________, the entire disclosure of which is hereby incorporated by reference
   - b. ☐ By inserting before the first line:
     This application claims the benefit of U.S. Provisional Application No. ____ ______, filed ______________, the entire disclosure of which is hereby incorporated by reference
   - c. ☐ Cancel claims _______

5. ☐ This application claims the benefit of Application Number _________ filed on ____ _________ in _________________ under 35 U.S.C. § 119, § 365(a), or § 365(b).
   (For originals)

6. ☐ Microfiche Computer Program (Appendix)

153(b)TRANS.DOC

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7. ☐ Recognize as an associate attorney ______, Registration No. __________

8. ☒ Address all future communications to:
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9. ☒ Fee Transmittal (duplicate enclosed)

(1) FOR	(2) NUMBER FILED	(3) NUMBER EXTRA	(4) RATE	(5) CALCULATIONS
TOTAL CLAIMS (37 CFR 1.16(c))	22- 20 =	2	X $ 18.00 =	$ 36.00
INDEPENDENT CLAIMS (37 CFR 1.16(b))	2 - 3 =	0	X $78.00 =	0
MULTIPLE DEPENDENT CLAIMS (if applicable) (37 CFR 1.16(d))			+ $270.00 =	0
			BASIC FEE (37 CFR 1.16(a))	$760.00
			Total of above Calculations =	$796.00
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11. ☒ The Assistant Commissioner is authorized to charge all additional required fees or to credit overpayments, to Deposit Account No. 19-1800, including fees required under 37 CFR 1.17

12. ☒ Accompanying Application Parts

a. ☐ Recordal of Assignment and Assignment
b. ☐ Information Disclosure Statement/PTO-1449
c. ☐ Preliminary Amendment
d. ☒ A self-addressed, stamped return receipt postcard to be returned with the filing date and Serial No. thereon
e. ☐ Certified copy of priority documents

Respectfully submitted,

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153(b)TRANS.DOC

TH 1457

DEHYDRATION OF GASES AT A WELLHEAD

FIELD OF THE INVENTION

The present invention relates to a method and apparatus for dehydrating or removing condensable hydrocarbons from produced vapors at a wellhead.

BACKGROUND TO THE INVENTION

Separators to remove water from gas as it is being produced are known, for example in US patent 5,444,684. This apparatus uses floating balls that float up and block a flowpath when a water level in the wellbore becomes high, and then as gas pressure builds, and forces the water level down, allowing production of gas that is free of liquid water. This apparatus is only capable of keeping liquid water out of produced gas. It is not capable of neither removing water from the wellbore, nor from lowering the dew point temperature of the produced gas.

US patent no. 5,794,697 also discloses a downhole separator for taking gas from a mixture of liquids and gas produced into a wellbore. This patent focuses on downhole compression of the gas and reinjection of the gas into a gas cap over the oil remaining in the formation. A separator is shown and described as a auger that imparts a swirling motion to the fluids, and then removal of the gas from the center of the swirl. This separator also does not lower the dew point temperature of the gas, but only separates existing phases.

Separators that are effective to lower dew points of gases generally require complex equipment and instrumentation,

such as refrigerated sponge oils or glycol absorbers. Such operations are generally too complex to be placed at wellheads such as sea floor wellheads, and too expensive to be place at individual wellheads in a gas producing field.

It would be desirable to have a dehydrator that not only removed liquid water, but that lowers the dew point temperature of the produced gas, and was simple and inexpensive. This is because as gas flows from the producing formation, it may be cooled by heat transfer to the more shallow formations surrounding the wellbore, and by adibatic expansion of the gas as it flows up the well. When the gas cools, water may then condense from the previously saturated gas stream.

Condensed water in produced gas could cause may problems. The separate liquid water phase could build up in low points in the gas collection system, and considerably increase the static head within the wellbore, and therefore reduce the well head pressure and/or gas production. Depending on the flow regime that results, the liquids could build up until the bottom of the wellbore is expose to a considerable additional liquid head. Also, the liquid water could combine with hydrocarbons and/or hydrogen sulfide to form hydrates in the collection system. These hydrates could plug the system. To prevent this, it is common to inject alcohols or gylcols into produced gas at the wellhead to prevent plugging with solid hydrates. This injection is relatively expensive, and further, results in more liquids being present in the wellbore. Spills of these liquids can be particular environmental concerns because they are by nature miscible with water.

Centrifugal force is useful for separation of liquids from streams of gases. Fluids, when rotating around a central axis will be accelerating toward the central axis, and inertia of the solids or liquids present will force the solids outward away from the central axis, against the flow of fluids. Fluids containing fewer liquids are then withdrawn from the center axis of rotation, and liquids are removed from the outer surface of the separator. The rate of flow of particles outward is limited by the resistance of the fluid. This rate dictated by Stokes Law. Practically, only about five micron sized particles can be separated by conventional cyclonic separators.

Dutch patent application No. 8901841 discloses a method of removing a selected gaseous component from a stream of fluid containing a plurality of gaseous components. The stream is induced to flow at a supersonic velocity through a conduit so as to decrease the temperature of the fluid in the conduit to below the condensation point of the selected component thereby forming condensed particles of the selected component. The conduit is provided with swirl imparting means to impart a swirling motion to the stream of fluid flowing at supersonic velocity. The condensed particles are extracted in a first outlet stream from a radially outer section of the stream and the remaining fluid is collected in a second outlet stream from a central part of the stream. The velocity in the radially outer section and in the central part of the stream is supersonic.

In an embodiment of the device for separating a gas from a gas mixture as disclosed in NL-8901841, separate shock waves occur in the first and second outlet streams, leading to a relatively large flow resistance of the fluid. Furthermore, the

separation efficiency is relatively low so that substantial amounts of the condensed particles are still present in the second outlet stream. This reference does not suggest utilizing such an apparatus for separation of gases within a wellbore.

SUMMARY OF THE INVENTION

In accordance with the invention there is provided a method and apparatus for removing water and/or condensable hydrocarbons from a produced gas at a wellhead, the method comprising the steps of:

- inducing the produced gas to flow at supersonic velocity through a conduit and thereby causing the fluid to cool to a temperature that is below a temperature at which water will begin to condense;
- inducing a swirling motion to the supersonic stream of fluid thereby causing the condensed water to flow to a radially outer section of a collecting zone in the stream;
- extracting the water and/or condensable hydrocarbons into an outlet stream from the radially outer section of the collecting zone; and
- transporting the produced gases from the wellhead which water and/or liquid hydrocarbons have been removed separately from the water and/or liquid hydrocarbons.

The apparatus is an apparatus effective for performance of this method.

In a preferred embodiment of the present invention, a shock wave caused by transition from supersonic to subsonic flow occurs upstream of the separation of the solids from the collecting zone. It was found that the separation efficiency is significantly improved if collection of the particles in the

collecting zone takes place after the shock wave, i.e. in subsonic flow rather than in supersonic flow. This is believed to be because the shock wave dissipates a substantial amount of kinetic energy of the stream and thereby strongly reduces the axial component of the fluid velocity while the tangential component (caused by the swirl imparting means) remains substantially unchanged. As a result the density of the particles in the radially outer section of the collecting zone is significantly higher than elsewhere in the conduit where the flow is supersonic. It is believed that this effect is caused by the strongly reduced axial fluid velocity and thereby a reduced tendency of the particles to be entrained by a central "core" of the stream where the fluid flows at a higher axial velocity than nearer the wall of the conduit. Thus, in the subsonic flow regime the centrifugal forces acting on the condensed particles are not to a great extent counter-acted by the entraining action of the central "core" of the stream. The particles are therefore allowed to agglomerate in the radially outer section of the collecting zone from which they are extracted.

Preferably the shock wave is created by inducing the stream of fluid to flow through a diffuser. A suitable diffuser is a supersonic diffuser. A diffuser may be, for example, a diverging volume, or a converging and then diverging volume.

In an advantageous embodiment, the collecting zone is located adjacent the outlet end of the diffuser.

The present invention may be practices in combination with other operations to effect drying of the fluid stream, or a separation of solids from the inlet stream by other means to decrease the load on the separator of the present invention.

Also, either of the stream containing the solids from the collecting zone or the stream from which the solids have been separated could be subjected to an additional separation step, for example, a dryer or separator.

The supersonic flow of the present invention also causes a rapid expansion, resulting in cooling of a compressible fluid stream. This cooling results in condensation of vapors to the extent that such cooling brings the temperature of the stream to a temperature below a dew point of the fluid stream.

Advantageously, any gaseous fraction separated from the radially outer section of the collecting zone can be recycled back to the inlet, preferably using an inductor to increase the pressure back to the pressure of the inlet stream.

Suitably the means for inducing the stream to flow at supersonic velocity comprises a Laval-type inlet of the conduit, wherein the smallest cross-sectional flow area of the diffuser is larger than the smallest cross-sectional flow area of the Laval-type inlet.

BRIEF DESCRIPTION OF THE FIGURES

FIG. 1 shows schematically a longitudinal cross-section of a first embodiment of the separator useful in the practice of the present invention.

FIG. 2 shows schematically a longitudinal cross-section of a second embodiment of the device useful in the practice of the present invention.

FIGS. 3A and 3B show schematically a devices according to the present invention at a wellbore.

FIG. 4 shows schematically an apparatus used to demonstate the device useful in the practice of the present invention.

FIG. 5 is a plot of particle size vs. equilibrium diameter for a selected set of conditions.

DESCRIPTION OF A PREFERRED EMBODIMENT

Copending US patent applications (Docket No. TH-1453 and TH-1454), both incorporated herein by reference, disclose various embodiments and variations of the present invention. In the disclosure of (TH-1454) a long expansion, leading to a relatively slower decrease of temperature as a function of time (dT/dt- in the order of less than 100,000 °C/second) is taught in order to form larger drops of condensable fluids. The larger drops are then more readily separated from the vapor stream.

In Fig. 1 is shown a conduit in the form of an open-ended tubular housing 1 having a fluid inlet 3 at one end of the housing. A first outlet 5 for solids laden fluid near the other end of the housing, and a second outlet 7 for substantially solids-free fluid at the other end of the housing. The flow-direction in the device 1 is from the inlet 3 to the first and second outlets 5, 7. The inlet 3 is an acceleration section containing a Laval-type, having a longitudinal cross-section of converging - diverging shape in the flow direction so as to induce a supersonic flow velocity to a fluid stream which is to flow into the housing via said inlet 3. The housing 1 is further provided with a primary cylindrical part 9 and a diffuser 11 whereby the primary cylindrical part 9 is located between the inlet 3 and the diffuser 11. One or more (for example, four) delta-shaped wings 15 project radially inward from the inner

surface of the primary cylindrical part 9. Each wing 15 is arranged at a selected angle to the flow-direction in the housing so as to impart a swirling motion to fluid flowing at supersonic velocity through the primary cylindrical part 9 of the housing 1.

The wings are preferably provided with a very sharp leading edge, most preferably razor sharp. At high velocities, a blunt edge can cause shock waves in front of the wing. This shock wave can decrease the lift forces dramatically. Because the energy imparted to the swirling motion is directly proportional to the lift force of the wing, it is preferred that this edge be sharp. The wing is also relatively flat, with a thickness preferably no more than about four millimeters at the base of the wing.

The diffuser 11 has a longitudinal section of converging - diverging shape in the flow direction, defining a diffuser inlet 17 and a diffuser outlet 19. The smallest cross-sectional flow area of the diffuser is larger than the smallest cross-sectional flow area of the Laval-type inlet 3.

The housing 1 further includes a secondary cylindrical part 17 having a larger flow area than the primary cylindrical part 9 and being arranged downstream the diffuser 11 in the form of a continuation of the diffuser 11. The secondary cylindrical part 17 is provided with longitudinal outlet slits 18 for liquid, which slits 18 are arranged at a suitable distance from the diffuser outlet 19.

An outlet chamber 21 encloses the secondary cylindrical part 17, and is provided with the aforementioned first outlet 5 for a stream of concentrated solid particles.

The secondary cylindrical part 17 debouches into the aforementioned second outlet 7 for substantially gas.

Normal operation of the device 1 is now explained.

A stream containing micron-sized solid particles is introduced into the Laval-type inlet 3. As the stream flows through the inlet 3, the stream is accelerated to supersonic velocity. As a result of the strongly increasing velocity of the stream, the temperature of the stream may decrease to below the condensation point of heavier gaseous components of the stream (for example, water vapors) which thereby condense to form a plurality of liquid particles. As the stream flows along the delta-shaped wings 15 a swirling motion is imparted to the stream (schematically indicated by spiral 22) so that the liquid particles become subjected to radially outward centrifugal forces. When the stream enters the diffuser 11 a shock wave is created near the downstream outlet 19 of the diffuser 11. The shock wave dissipates a substantial amount of kinetic energy of the stream, whereby mainly the axial component of the fluid velocity is decreased. As a result of the strongly decreased axial component of the fluid velocity, the central part of the stream (or "core") flows at a reduced axial velocity. This results in a reduced tendency of the condensed particles to be entrained by the central part of the stream flowing in the secondary cylindrical part 17. The condensed particles can therefore agglomerate in a radially outer section of a collecting zone of the stream in the secondary cylindrical part 17. The agglomerated particles form a layer of liquid which is extracted from the collecting zone via the outlet slits 18, the outlet chamber 21, and the first outlet 5 for substantially liquid.

The stream from which water has been removed (and any condensable vapors) is discharged through the second outlet 7 for substantially solids-free gas.

In Fig. 2 is shown a second embodiment of the device for carrying out the invention, the device having an open-ended tubular housing 23 with a Laval-type fluid inlet 25 at one end. A first outlet 27 for a stream containing liquids at the other end of the housing. The flow-direction for fluid in the device is indicated by arrow 30. The housing has, from the inlet 25 to the liquid outlet 27, a primary substantially cylindrical part 33, a diverging diffuser 35, a secondary cylindrical part 37 and a diverging part 39. A delta-shaped wing 41 projects radially inward in the primary cylindrical part 33, the wing 37 being arranged at a selected angle to the flow-direction in the housing so as to impart a swirling motion to fluid flowing at supersonic velocity through the housing 23. A tube-shaped second outlet 43 for substantially gas extends through the first outlet 27 coaxially into the housing, and has an inlet opening 45 at the downstream end of the secondary cylindrical part 37. The outlet 43 is internally provided with a straightened (not shown), e.g. a vane-type straightener, for transferring swirling flow of the gas into straight flow.

The delta-shaped wing is preferably a triangular profile shape, with a leading edge that is sloped to a wing tip so that the leading edge is "subsonic". A subsonic leading edge is one wherein "mach" line extending from the base of the wing is at greater angle from the cord of the wing at the base than the leading edge of the wing (i.e., the wing is not within its own shock wave). The trailing edge is preferably also subsonic. The

wing preferably extends across the vortex tube or conduit for about two thirds of the diameter.

Normal operation of the second embodiment is substantially similar to normal operation of the first embodiment. A supersonic swirling flow occurs in the primary cylindrical part 33, the shock wave occurs near the transition of the diffuser 35 to the secondary cylindrical part 37. Subsonic flow occurs in the secondary cylindrical part 37, the stream containing the solid particles and any condensed liquids is discharged through the first outlet 27. Dried gas is discharged through the second outlet 43 in which the swirling flow of the gas is transferred into straight flow by the straightener.

In the above detailed description, the housing, the primary cylindrical part, the diffuser and the secondary cylindrical part have a circular cross-section. However, any other suitable cross-section of each one of these items can be selected. Also, the primary and secondary parts can alternatively have a shape other than cylindrical, for example a frusto-conical shape. Furthermore, the diffuser can have any other suitable shape, for example without a converging part (as shown in Fig. 2) especially for applications at lower supersonic fluid velocities.

Instead of each wing being arranged at a fixed angle relative to the axial direction of the housing, the wing can be arranged at an increasing angle in the direction of flow, preferably in combination with a spiraling shape of the wing. A similar result can be obtained by arranging flat wings along a path of increasing angle with respect to the axis of initial flow.

Furthermore, each wing can be provided with a raised wing-tip (also referred to as a winglet) Preferably this winglet is bent with respect to the surface of the wing by an angle of about 90°.

Instead of the diffuser having a diverging shape (Fig. 2), the diffuser alternatively has a diverging section followed by a converging section when seen in the flow direction. An advantage of such diverging - converging shaped diffuser is that less fluid temperature increase occurs in the diffuser.

Referring now to FIG. 3A, an apparatus of the present invention is shown schematically at a subsea wellhead. A subsea well 301, in a body of water 313 is shown with a casing 302, with perferations 303 providing communication from a formation 312 to the inside of the wellbore 304. Typical well head equipment 305 is schematically shown. The separator of the present invention 306 separates a mostly liquid stream 307 from a dried stream of vapors 308. Temperatures at the sea floor 309 approach freezing temperatures, and formation of hydrates along sea floor piping is therefore a serious concern. The present invention provides a simple, low maintenance and inexpensive dehydration system. The seprated liquids may be provided with hydrate inhibition additive 310 through a controlled injection 311.

Referring now to FIG. 3B, another embodiment is shown, with a wellbore 350 located at a surface 351. The wellbore is cased with a casing 354 provided with perforations 355. Typical wellhead equipment may be provided 352. A liquid-vapor separator 353 is provided with a liquid outlet 356 and a level control system 357. A vapor outlet from the liquid-vapor separator 363 is routed to the dehydrator of the present invention 358. The

vapors from the outlet 359 of the separator of the present invention is dry gas 360 having a dewpoint lower than the dewpoint of the produced gases. Liquid from the separator of the present invention 364 may contain vapors, which will be saturated, and are therefore preferably routed to a second vapor-liquid separator 361. The liquids from this second separator 362 can be combined with liquids from the first separator, or routed separately to surface equipment. Alternatively, liquids from the second separator may be reinjected into a formation for effective disposal. The liquids from the second separator may be pumped to a higher pressure resevoir, or flow by pressure available to a low pressure formation. The liquids from the second separator, if reinjection is desirable, may be collected and then reinjected, or reinjected into the wellbore from which the gas was produced.

Vapors from the second liquid-vapor separator 365 may be recycled through a venture recompression nozzle into the inlet of the separator of the present invention.

The stream concentrated in water and condensable hydrocarbons 364 is preferably sufficiently concentrated in water vapor so that addition of components to prevent formation of hydrates is not needed. Even if hydrate inhibition is desirable, the amount of hydrate inhibition compound needed will be considerably reduced because of the need to treat only the smaller volume of fluid to be treated.

To increase the size of the condensed particles, the boundary layer in the supersonic part of the stream can be thickened by, for example, injecting a gas into the supersonic part of the stream. The gas can be injected, for example, into

the primary cylindrical part of the housing via one or more openings provided in the wall of the housing. Suitably part of the gas from the first outlet is used for this purpose. The effect of such gas-injection is that less condensed particles form in the supersonic part of the stream resulting in larger particles and better agglomeration of the larger particles.

The swirl imparting means can be arranged at the inlet part of the conduit, instead of downstream the inlet part.

EXAMPLE

A test apparatus for the present invention was prepared, and demonstrated for separating water vapor from air at ambient conditions. Fig. 4 is referred to for the general configuration of the apparatus used.

In this example the air 425 is pressurized to 1.4 bar(abs.) by means of a blower 401 to provide pressurized air 426. After the blower the air is cooled to about 25 to 30 ^{o}C by fin cooler 402, located in a vessel 418, and water 419 is sprayed into the vapor space below the cooler 420 to ensure that the air is near water saturation (RV = 90%). This water saturated air 427 is fed to the feed liquid-vapor separator 403 where the water is separated with a small amount of slip air into a wet stream 421, coming along with this water liquid stream and dried air 422.

In this example, the apparatus is provided with tubular flow ducts although the same results can be achieved for rectangular or asymmetric duct cross sections. Therefore diameters of devices are mentioned and always refer to the inner diameter.

The typical inlet conditions are summarized below:

1. Mass flow rate : 1.2 kg/s
2. Inlet pressure : 1400 mbar(abs)

3. Inlet temperature : 25 ^{o}C

4. Inlet humidity : 90 %

The device condenses water vapor, resulting in a mist flow containing large number of water droplet, typically $10^{13}/m^{3}$. Therefore the final temperature (T) and pressure (P) at the outlet of the Lavel nozzle and through the supersonic region have to be determined such that the water vapor fraction becomes negligible small. In this case it will be T = -28 ^{o}C and P = 680 mbar(abs.) in the supersonic zone 428.

The nozzle throat cross-section is sized in order to obtain the required flow rate. Considering the inlet conditions required to result in sufficient separation of condensable, this throat diameter 404 is 70 mm. The inlet diameter 405 is 300 mm, although its value is not significant with respect to the working of the apparatus. The nozzle outlet diameter 400 is 80 mm in order to obtain supersonic flow conditions; typically the corresponding Mach number, M = 1.15.

The lengths of the nozzle are determined by the cooling speed, which for this case is 19000 K/s. Persons of ordinary skill in the art can determine pressure and temperature profiles for the flow through the apparatus, and thus the cooling rate. The cooling speed determines the droplet size distribution. Lowering the value of the cooling speed results in larger average droplet sizes. The of the nozzle are:

L1, 406 : 700 mm : from nozzle inlet to nozzle throat

L2, 407 : 800 mm : from nozzle throat to nozzle outlet

In order to decrease frictional losses the wall roughness is small, preferably 1 micron or less.

Depending on the application any rigid material can be used for the nozzle device, as long as the before mentioned design parameters are respected.

The vortex tube 408 is connected between the nozzle outlet and the diffuser. In the vortex tube a wing-like, swirl imparting internal 409 is present. At the edge of this internal a vortex is created on the upper (low-pressure) side and shed from the plane, preferably at the trailing edge. The root cord of this wing-like plate is attached to the inner wall of the vortex tube.

The sizing of the vortex tube is related to the nozzle outlet diameter, which is the inlet diameter of the vortex tube 400 is 80 mm. In this case vortex tube is slightly conical; the diameter is increasing linear to 84 mm (423) over a length of approximately the cord length of the wing.

After the conical section of the vortex tube 410, the vortex tube diameter is constantly 84 mm over a length were the droplets will be depositing on the inner wall (separation length). These two lengths are:

L3, 410 : 300 mm : from wing apex to wing trailing edge
L4, 412 : 300 mm : from wing trailing edge to diffuser

The sizing of the wing internal depends on the preferred circulation or integral vorticity. This circulation is typical 16 m^2/s resulting from a wing cord length of 300 mm, a wing span at the trailing edge is 60 mm and at an incidence of the wing cord at the axis of the tube of 8^o. The sweepback angle of the leading edge (from perpendicular to the flow) is 87^o and the sweepback angle of the trailing edge is 40^o. The edges of the wing are sharp. The plane of the wing is flat and its profile is

extremely slender. The thickness of the wing is about 4 mm at the root. The wing is at an 8° angle to the axis of the tube.

In the drainage section withdrawal of liquids out of the vortex tube is achieved. The drainage section is not a sharp distinguished device but is an integral part of the vortex tube, by means of, for example, slits, porous materials, holes in the vortex tube walls; or, as shown in FIG. 4, is an integral part of the diffuser by means of a vortex finder 413 (co-axial duct). In this example, a vortex finder (co-axial duct) is placed centrally in the duct after the shock wave, which is present directly after the vortex tube in the first diffuser part 414.

The sizing of the vortex tube is dependent on the diameter ratio between diffuser diameter at that location 424(90 mm at the inlet) and vortex finder inlet diameter at that point 425(85 mm at the inlet). The cross-sectional area difference between the latter two determines the minimal flow, which is extracted from the main stream containing the liquids. In this case this minimal flow is 10% of the main flow i.e. 0.12 kg/s. The diffuser length 433 is 1500 mm.

In the diffuser the remaining kinetic energy in the flow is transformed to potential energy (increase of static pressure). It is desirable to avoid boundary layer separation, which can cause stall resulting in a low efficiency. Therefore the half divergence angle of the diffuser should be preferably less then 5^o as in this case 4^o is used. The diffuser inlet diameter is the same as the vortex finder inlet diameter (85 mm). The outlet diameter 415 of the diffuser is 300 mm, and the dry air at this point is at about atmospheric pressure. The performance of this apparatus was measured by two humidity sensors (capacitive

principle: manufacturer 'Vaisala') one at the air inlet 416 and the other at the dried air outlet 417, both were corrected for temperature and pressure. The typical values of the inlet water fractions were 18-20 gram of water vapor per kg dry air. Typical values of the outlet water were 13-15 gram of water vapor per kg dry air. This can be expressed in separation efficiencies of about 25% of the water vapor in the inlet removed. This also corresponds to the separation of liquids condensed in the super sonic region, because most of the liquid water present in the inlet stream condenses at that point.

Separation in the apparatus of the present invention is due to inertia forces of a dispersed liquid phase transported in a gaseous fluid. A swirling motion of the fluid (vortex flow) imparts inertia forces in which the heavier constituent's i.e. liquid particles, drifting in outer radial direction with respect to the gas streamlines.

Particle drift in gravitational or centrifugal fields is described by Stokes relationships, solving the momentum equations. In a vortex two counteracting phenomena - with respect to the forces acting on said particle - taking place known as: Vortex strength (Γ) and Sink strength (Q). The vortex strength (Γ) forces the particle to flow in tangential direction causing a centrifugal force acting on this particle so a positive radial drift of the particle results. The sink strength (Q) causes a radial inflow of gas to the vortex axis, resulting in a negative radial drift of the particle. For every vortex there exists a radial position for a particle in the vortex where the resulting force acting on the particle is zero. On this particular radial position - known as the equilibrium radius

(R_{eq}) - the particle has no motion in radial direction anymore. When R_{eq} exceeds the conduit radius ($R_{conduit}$) the droplet is deposited on the wall, which enables separation of liquids. From Stokes law it is known that:

$$R_{eq} = \frac{\Gamma}{\sqrt{Q}} \cdot \sqrt{2\pi \cdot \tfrac{2}{9} \cdot \frac{d^2}{4\pi^2 \nu} \cdot \left(\frac{\rho_L}{\rho_G} - 1\right)}$$

and:

$$Q = 2\pi r V_{rad.}$$

$$\Gamma = 2\pi r V_{tan.}$$

wherein: r is the radius from the center of the vortex;

$V_{rad.}$ is the velocity radially toward the axis of rotation of the vortex; and

$V_{tan.}$ is the tangential velocity of the fluid.

Separation is achieved when: $R_{eq} \geq R_{conduit}$.

The sink strength Q is typically between about 1 and about 5 percent of the circulation in vortexes utilized in the present invention. Therefore:

$$Q = 2\pi r V_{rad.} \approx (0.01)\Gamma = (0.01) 2\pi r V_{tan.}$$

Fig. 5 shows the minimal $R_{conduit}$ as function of the particle diameter (d) for conditions of:

Circulation	: Γ =	48.3	m^2/s
Sink strength	: Q =	0.5	m^2/s
Kinematic viscosity	: ν =	$1.5.10^{-5}$	m^2/s
Gas density	: ρ_G =	0.3	kg/m^3
Particle density	: ρ_L =	1000	kg/m^3

This figure shows that for a particle diameter of 1 um the maximum allowable conduit radius should be equal to or less then 200 mm in order to get separation ($R_{eq} \geq R_{conduit}$).

We claim:

1. A method for removing water and/or condensable hydrocarbons from a produced gas at a wellhead, the method comprising the steps of:

- inducing the produced gas to flow at supersonic velocity through a conduit and thereby causing the fluid to cool to a temperature that is below a temperature at which water will begin to condense;

- inducing a swirling motion to the supersonic stream of fluid thereby causing the condensed water to flow to a radially outer section of a collecting zone in the stream;

- extracting the water and/or condensable hydrocarbons into an outlet stream from the radially outer section of the collecting zone; and

- transporting the produced gases from the wellhead which water and/or liquid hydrocarbons have been removed separately from the water and/or liquid hydrocarbons.

2. The method of claim 1 further comprising the step of: creating a shock wave in the stream so as to decrease the axial velocity of the fluid to subsonic velocity wherein extraction water into an outlet stream from the radially outer section of the collecting zone is upstream of the shock wave and downstream the location where the swirling motion is imparted.

3. The method of claim 1 wherein the shock wave is created by inducing the stream of fluid to flow through a diffuser.

4. The method of claim 1 wherein the wellhead is a subsea wellhead.

5. The method of claim 1 wherein the water and/or condensable hydrocarbons extracted into an outlet stream from the

radially outer section of the collecting zone are separated into a vapor phase and a liquid phase in a separator.

6. The method of claim 1 further comprising the step of recycling the vapor phase from the separator back to the produced gas to flow prior to the produced gas flow being induced to flow at supersonic velocity through a conduit.

7. The method of claim 1 further comprising adding a hydrate inhibition component to the outlet stream extracted from the radially outer section of the collecting zone.

8. The method of claim 1 wherein the swirling motion is imparted by a wing placed in the supersonic flow region.

9. A wellhead apparatus for producing gas from a subsea formation, the wellhead comprising:

an acceleration section wherein gas from the subterranean formation is accelerated to a supersonic velocity;

a swirl imparting section that imparts a swirling motion to the gas;

a collection zone from which a gas stream containing reduced water content is removed; and

a radially outer section of the collecting zone with a radially outer section from which water can be collected.

10. The wellhead of claim 9 further comprising a shock wave initiator downstream of the swirl imparting section.

11. The wellhead of claim 10 wherein the shock wave initiator is a diffuser.

12. The wellhead of claim 10 wherein the shock wave initiator is located so that the shock wave is upstream the collecting zone.

13. The wellhead of claim 10, wherein the shock wave is induced by a diffuser.

14. The wellhead of claim 13, wherein the acceleration section comprises a Laval-type inlet of the conduit, and wherein the smallest cross-sectional flow area of the diffuser is larger than the smallest cross-sectional flow area of the Laval-type inlet.

15. The wellhead of claim 9 wherein said collecting zone is located adjacent the outlet end of the diffuser.

16. The wellhead of claim 9 wherein the gas containing reduced amount of water is collected in a vortex catcher.

17. The wellhead of claim 9 wherein the swirl imparting section that imparts a swirling motion to the stream comprises a wing device.

18. The wellhead of claim 17 wherein the wing is a triangular shape wing at an angle to the axial flow of supersonic fluids of between about 4 and 12 degrees.

19. The wellhead of claim 18 wherein the leading edge of the wing is at an angle to the axial flow that results in a subsonic leading edge.

20. The wellhead of claim 19 wherein the trailing edge of the wing is at an angle to the axial flow that results in a subsonic trailing edge.

21. The wellhead of claim 20 wherein the wing has an increasing angle with respect to the direction of axial flow between the leading edge and the trailing edge.

22. The wellhead of claim 18 wherein the wing includes an end piece that is at about a 90 degree angle to the surface of the wing.

A B S T R A C T

DEHYDRATION OF GASES AT A WELLHEAD

A method and apparatus are provided for removing water and/or condensable hydrocarbons from a produced gas at a wellhead, the method including the steps of: inducing the produced gas to flow at supersonic velocity through a conduit and thereby causing the fluid to cool to a temperature that is below a temperature at which water will begin to condense; inducing a swirling motion to the supersonic stream of fluid thereby causing the condensed water to flow to a radially outer section of a collecting zone in the stream; extracting the water and/or condensable hydrocarbons into an outlet stream from the radially outer section of the collecting zone; and transporting the produced gases from the wellhead which water and/or liquid hydrocarbons have been removed separately from the water and/or liquid hydrocarbons. The apparatus is an apparatus effective for performance of this method.

Fig.1

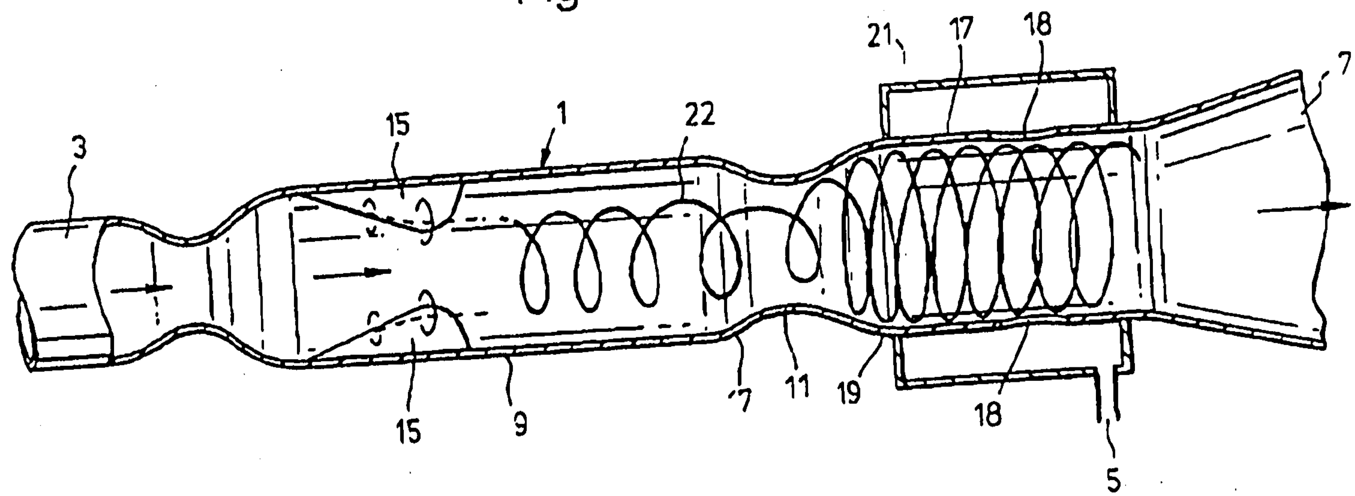
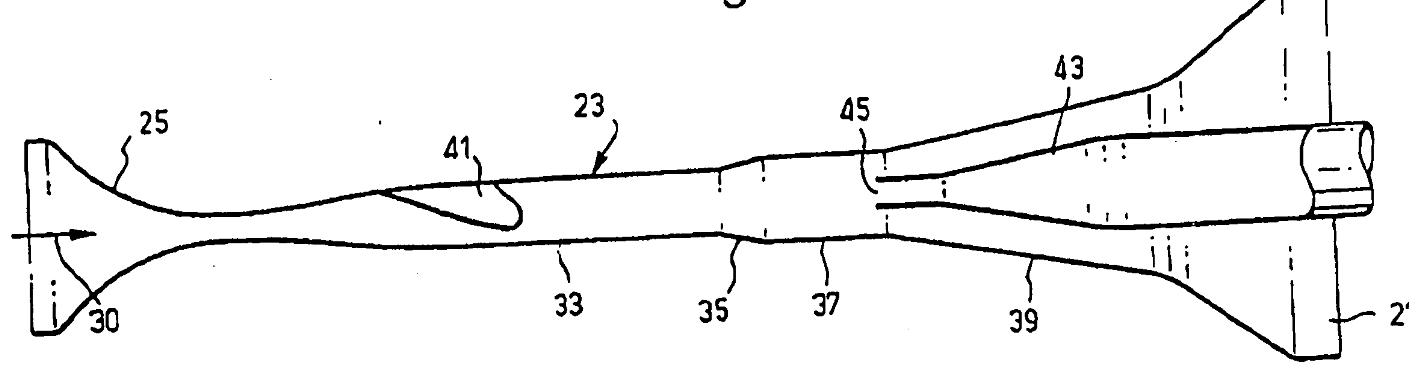


Fig.2.



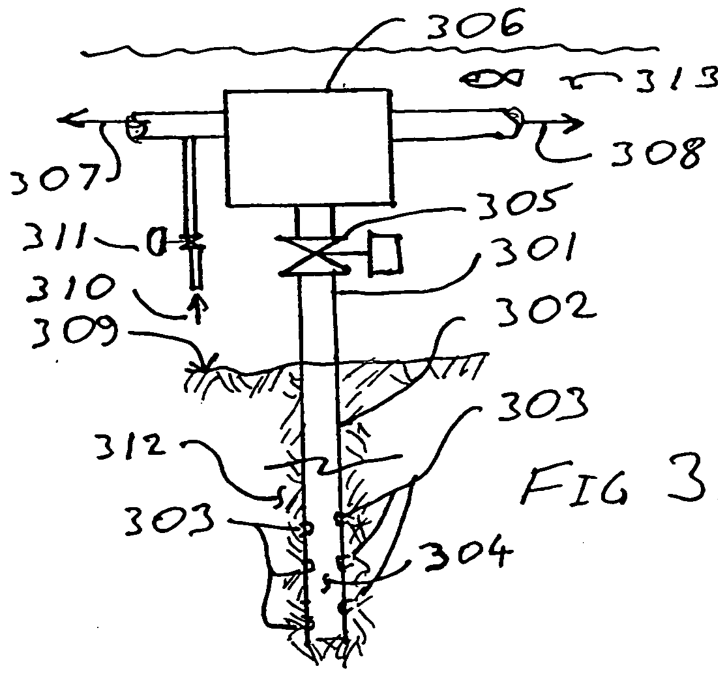

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FIG 3A

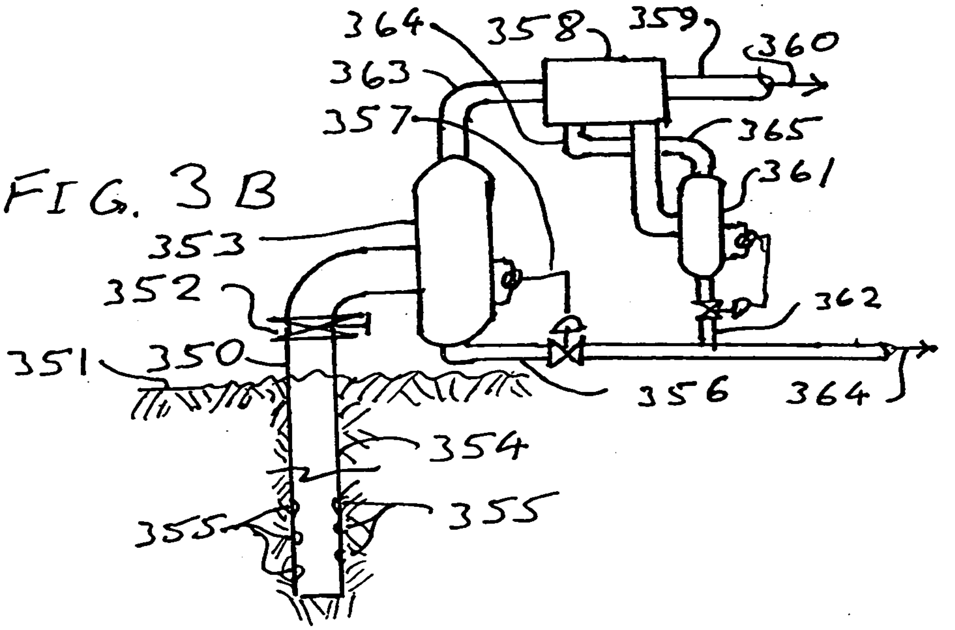
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FIG. 3B

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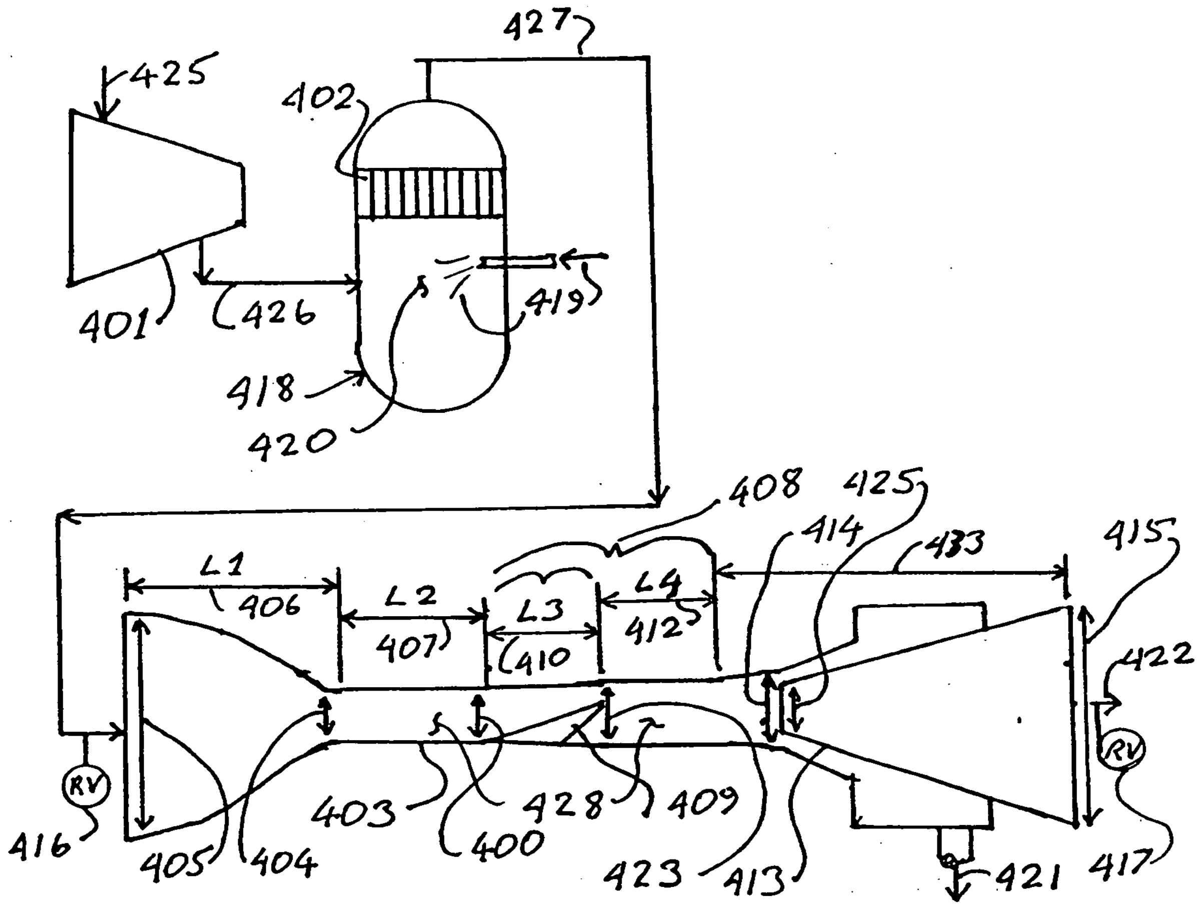

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L3
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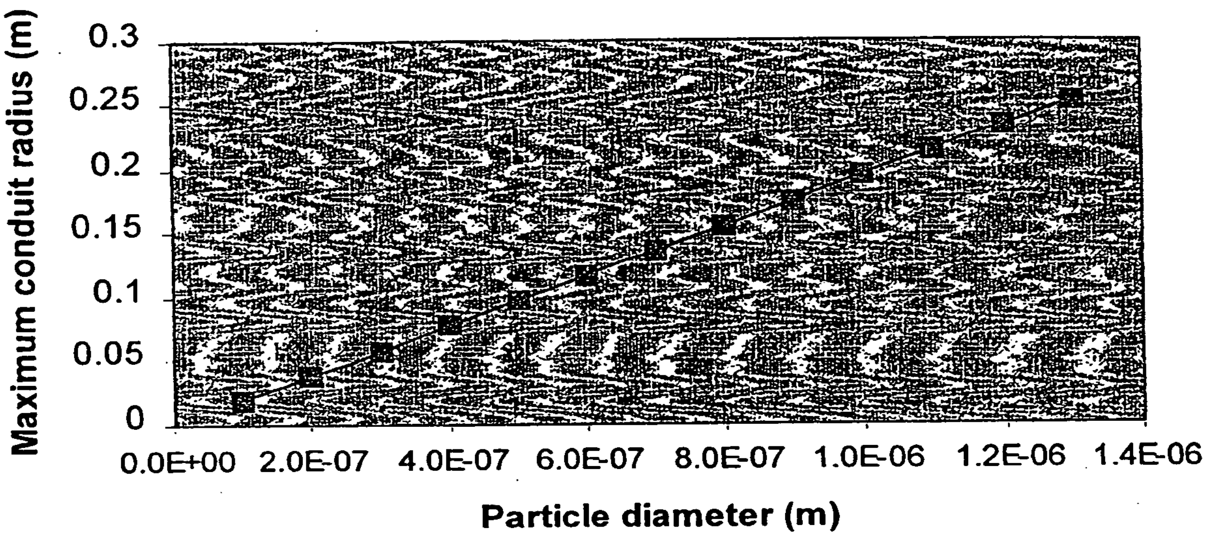
FIG. 4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0.3
0.25
0.2
0.15
0.1
0.05
0
0.0E+00
2.0E-07
4.0E-07
6.0E-07
8.0E-07
1.0E-06
1.2E-06
1.4E-06
Particle diameter (m)

FIG. 5